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Neutrino oscillations along the Earth to probe flavor parameters: a *NeuWorld*

Daniele Fargion and Daniele D'Armiento

Physics Dept. University Rome University, Sapienza; Ple.A.Moro 5,00185,Rome,Italy; INFN Rome 1

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Abstract

On 2010 MINOS experiment was showing an hint of possible different mass splitting and mixing angles for neutrinos and anti-neutrinos, suggesting a charge-parity-time (CPT) violation in the lepton sector; later on last year 2012 a second result from MINOS showed a reduced discrepancy between the two set of parameters, nearly compatible with no CPT violation. We proposed an experiment for more precise estimation of neutrino and $\nu-\bar{\nu}$ oscillation parameters being useful not only for a complete discrimination for CPT scenarios, but also for mass hierarchy and θ_{13} determination, and mostly for the first oscillated detection of tau , ν_τ and $\bar{\nu_\tau}$, neutrinos. Indeed, the last a few years of OPERA activity on the appearance of a τ lepton still has not been probed convincingly. Moreover atmospheric anisotropy in muon neutrino spectra in IceCube DeepCore, at $\cong$ 10 GeV, can hardly reveal asymmetry in the $\nu_\mu - \bar{\nu_\mu}$ oscillation parameters nor the tau and anti tau appearance. We show an experiment, (the longest baseline neutrino oscillation test available by crossing most of Earth's diameter, a *NeuWorld*), that may improve the oscillation measurement and disentangle at best any hypothetical CPT violation while testing τ and $\bar{\tau}$ appearance at the same time of the $\nu_\mu - \bar{\nu}_\mu$ disappearance correlated. The experiment use a neutrino beam crossing the Earth, within an OPERA-like experiment from CERN (or Fermilab), in the direction of the IceCube DeepCore detector at the South Pole. Such a tuned beaming and its detection may lead to a strong signature of neutrino muon-tau mixing (nearly one $\bar{\tau}$ or two τ a day, with 10σ a year), even for an one per-cent OPERA-like experiment.

Keywords:

1. Introduction

The MINOS 2010 observations [3] seemed to imply (or now at least to marginally hint [4]) a different anti-neutrino mass splitting with respect to well known neutrino one, leading to a possible CPT violation. Even a marginal neutrino anti-neutrino mass difference may open new roads in our particle physics understanding [5]. This CPT violation might indicate a very peculiar role of neutral leptons in matter/anti-matter genesis, and it may address unsolved lepton-baryon-genesis open puzzle, related to cosmological mysteries. Consequently such a tiny CPT violation, if confirmed, might become one or the main (amazing) discovery of the century: therefore we inquire how at best CPT violation may be observed. In order to do that we proposed two ways: (1) exploiting current and coming soon atmospheric data from IceCube DeepCore detector, and (2) considering a completely new neutrino oscillation baseline. Such experiment should beam neutrinos across the whole Earth: *NeuWorld*[2], and it is almost ready since both accelerator and detector already exist suitable for that. Only a new tunnel, Opera-like, is necessary.

2. A road map to disentangle mixing flavors

We considered first the ongoing experiment based on atmospheric neutrino signal in DeepCore that may be a benchmark for CPT scenario disentangling; we underline that the smeared muon track energy measure and the angular resolution can confuse any tiny CPT anisotropy in Deep Core spectra (Fig 1); such smeared anisotropies might be not clearly detected by present at-

mospheric neutrino records in Deep Core. Only a negligible difference would rise in the low channel muon tracks by allowable CPT violation, as shown in Fig. 1. On the contrary the common muon disappearance (as the SK observation) will be anyway observable.

Therefore we focus here on a future possible ad-hoc Very Long Baseline experiment able to sharply confirm even tiny CPT violation in a very short time and in an accurate way. We studied the appearance of muon neutrino by $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ oscillations, in the energy-distance range where CPT conserved oscillation is almost vanishing, while CPT violated oscillation is (partially) allowed, based on the experimental parameters determined by MINOS. By doing this we will be able also to test with great accuracy the $\nu_\mu \to \nu_\tau$, and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ mixing, leading also to a very precise estimate of their mixing parameters that may shed also light to a possibly hidden symmetry unwritten into a tuned value: $\sin(2\theta_{23}) \simeq 1$.

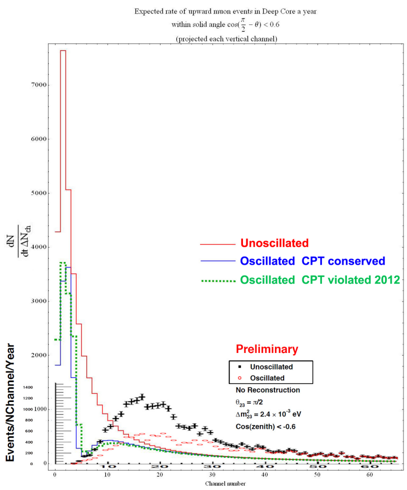

Figure 1: Our expected atmospheric neutrino spectra in DeepCore, as a function of the DOM channel number, for the latest (2012) neutrino oscillation parameters. Here we apply the Earth-matter influence along the overall oscillation vs. the DeepCore preliminary expectations (2009 − 2010),[8, 9]. The green dotted curve (oscillation in case of CPT violation) is very close to the CPT-conserved rate denoted by the thin blue line. They are to be compared to DeepCore small red ovals estimation, by [8], which has been used and shown here as a reference benchmark. While the CPT deviation in 2010 was, in principle, well detectable because of a 30% suppression (with respect to the CPT-conserved case, [2]) around channels 8 - 12, now a small CPT deviation, as in 2012 MINOS data, is almost unobservable. Note that our predictions rate shown by blue and green dots at channels above 20 (corresponding after geometry projection to nearly 70-80 GeV neutrino energy) are nearly half of the corresponding ones in Deep Core foreseen event rate (shown as small red circles). This discrepancy might be observable as soon data will be released.

We performed an estimation for other experiment such as OPERA, [1] at Gran Sasso, for calibration. A common shortcoming of most baseline experiments (thousand or hundreds km ν flight) is the very unefficient flavour conversion probability and the usual low neutrino energy. The higher the energy, the larger the distance needed to complete a mixing oscillation, but also the better the beaming, (because of the higher Lorentz factor of pion decay), as well as the larger the neutrino cross-section. Incidentally the approximate beaming solid angle shrinks by a factor proportional to E_π^2, and the neutrino-matter cross-section grows as E_ν providing a global signal enhancement amplified by a factor proportional to $\sim E_\nu^3$. Therefore a long-baseline experiment for instance as in our *NeuWorld*[2] experiment at 22 GeV, may play a better role (8000 times better than 1 GeV experiment) to define oscillation parameters. Moreover the dilution factor due to the much greater distance from CERN of DeepCore than OPERA [1], a factor $\simeq$ 240, is widely compensated by the detector mass ratio (DeepCore versus OPERA), at least by a factor $\simeq$ 4800, implying a benefit of a factor $\simeq$ 20. In addition the larger distance in the *NeuWorld*[2] baseline offers a complete $\nu_\mu \leftrightarrow \nu_\tau$ conversion with respect to 1.5% of OPERA, providing a further gain of an additional factor $\simeq$ 60. All together the advantages of a long baseline experiment with DeepCore (respect to OPERA) in tau appearance, is a factor of about or above 2400; moreover all the born τ (within the limited 4.8 Mton DeepCore) will be observable (contrary to OPERA), leading to an efficiency ratio 15 : 1 for *NeuWorld*, leading to an exceptional ratio 36000 between *NeuWorld* and OPERA [1] in testing tau appearance. One tau a day in our scenario even for just at 1% OPERA size *NeuWorld* experiment versus one rare tau a year in present OPERA experiment (see more precise details in next Tables). We remind that we are considering half detection volume respect the one claimed, just for prudential reasons [6, 7].

Our main proposal therefore stands for building a baseline from CERN (or FNAL) to IceCube DeepCore detector, at $E_\nu \sim 20$ GeV, with more than 4 MegaTon detection mass. SuperKamiokande detector was also considered, but found to be not enough in terms of signal intensity, in comparison to DeepCore.

Therefore we estimated in detail, for each source (CERN or FNAL), for each Proton On Target source flux (and its secondary neutrino flux) and for each detector distance (SK or IceCube), the results (muons or tau events) by a chain of neutrino-signal values source-propagation-flavor mixing and oscillation in Earth, the detection rate in volume inside or outside the detector.

Each value or formula is deeply correlated to the previous one, leading to a realistic estimate of muon or anti-muon signals (as well as tau-anti tau), designed at best to disentangle the hypothetical CPT asymmetry as well as to fix with high accuracy muon-tau flavor mixing parameters.

3. *NeuWorld*:Neutrino events in longest baselines

In figure 2 we show muon neutrino oscillation probability versus neutrino energy, for the two set of parameters, conserving and violating CPT, that is assuming the same parameters for both $\nu - \bar{\nu}$ (under CPT conserved case) and different parameters between ν and $\bar{\nu}$ (under CPT violated case). It is clearly visible that in the eventual CPT violated scenario, a different oscillation for ν_μ and $\bar{\nu}_\mu$ would result, leading to a discrepancy in the event number, while this would not be for usual symmetry between matter and anti-matter. Therefore we suggest this new $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance experiment, and propose various longest baselines, for which both source and detector are already available. All considered baselines are listed in table 1.

The method of estimating the beaming and detection of neutrinos to detectors (DeepCore or SuperKamiokande) is based on a chain of correlated evaluations that we used and calibrated with known experiments: OPERA and MINOS. By evaluating the chord distance and the appropriate energy enhancing neutrino oscillation, we find ν_μ event rate as would be no oscillation, in comparison to known rates in OPERA for instance, using the same p.o.t. number (table 1). The energy is chosen as to maximize ν_μ disappearance, so that any eventual different $\bar{\nu}_\mu$ oscillation probability (in CPT violated case) would be clearly visible over a nearly null background. We do remind that because accurate timing in sending neutrino bunches along the Earth one may easily cancel any rare upward atmospheric neutrino noise, also because of the selected narrow angle arrival direction.

We always take in consideration the flavor neutrino mixing within the Earth, keeping care of the exact step by step variability of the inner matter density. At energies $\geq$ 20 GeV, nevertheless, the flavor mixing along the Earth diameter is not very much different from the vacuum case, but we did take into account of it.

In table 2 we consider the primary bunch bending and tunnel parameters, for a 1 Tesla magnetic field curving a pion beam at nearly 50 GeV energy. In the most economic version the whole tunnel arc with the rectilinear sector length will be less than 200 m underground. This tunnel cost is the only expenses needed to invest to achieve a the *NeuWorld* experiment. Detectors (Deep Core) and accelerators (CERN or FNL) already exist.

In figure 3 it is shown how oscillation probability is averaged by a non-monochromatic ($\Delta E/E = 20\%$) neutrino beam. The presence of such energy smearing increases the noise and reduces the signal significance. This severe noise is usually ignored by most of the other author papers. However, as discussed in the following tables, the event rate in the worst 1% OPERA-like experiment may lead to a remarkable 6σ signal detection of any tiny (MINOS 2012) hypothetical CPT violation within a year of detection.

In table 3 we take in account the averaged oscillation probability and obtain the resulting event for ν_μ and $\bar{\nu}_\mu$; the latter $\bar{\nu}_\mu$ is described both for conserved or violated CPT scenarios. These events are compared to a OPERA-like experiment at 100% (decay length and neutrino flux) , while in table 4 it is shown a severe economic reduction 1% because a 5% shorter pion decay length and additional 20% due to considering a lower ν_μ intensity flux, since our proposed beam select pion flux by a spectrometer energy filter while bending the bunch.

The (preliminary) correlated parameter map derived by a year of recording (in a minimal 1% OPERA beaming experiment) is shown in Figure 4.

We also underline the ν_τ appearance, so that our experiment *NeuWorld* has another important return: this will be able to detect nearly 2 τ a day, or 1 $\bar{\tau}$ as seen in table 5 and 6. The noise of Neutral Current events was considered as background, leading nevertheless to a 14 σ for tau appearance and 10 σ for anti-tau appearance.

Muon Neutrino beam events by
$3.5 \cdot 10^{19}$ proton on target(p.o.t) a year from CERN or FNAL

Baseline	distance (km)	E_ν (GeV)	$\left(\frac{L'}{L}\right)^2$	Mass detector *kton*	$N_{ev\mu_{CC}}$ no osc. $year^{-1}$
CERN–OPERA	$L = 732$	17	1	1.2	2847
CERN–SK	$L' = 8737$	15.8	142.5	22.5	324
Fermilab–SK	$L' = 9140$	16.5	155.9	22.5	341
CERN-IceCube	$L' = 11812$	21.8	260.4	4800	93343
Fermilab–IceCube	$L' = 11623$	21.4	252.1	4800	93951

Table 1: Source detector distances, tuned energies, flux dilution, event rate, in comparison with the OPERA baseline.

4. Conclusion

Our recent proposal, *NeuWorld* experiment [2] shows the estimated ν_μ ν_τ event rates (and the same for the anti-particles) for two main neutrino baselines and configurations (CERN (or Fermilab) to ICECUBE); the experiment is offering a high rate of detection of muon dis-

Baseline	E_ν (GeV)	Angle (deg)	Arc Depth (m)	Tunnel length $L_{5\%}$ (m)	Tunnel depth $H_{5\%}$ (m)
CERN–SK	15.8	43.19	34.2	50	34
Fermilab–SK	16.5	45.77	40	55	40
CERN-IceCube	21.8	67.82	106.3	92	85
Fermilab–IceCube	21.4	65.67	99.5	90	82

Table 2: Beaming, bending and tunnel parameters: final neutrino energy, bending angle (for 1T magnetic field), beam bending arc depth, decay tunnel length and depth in an economic scenario, considering shorter pion decay tunnel length, that is 5% decay length respect the OPERA one (1 km), for the same neutrino flux.

Baseline	N_{ν_μ} / $N_{\bar{\nu}_\mu}$ no osc. inside and outside	$\langle P_{\mu\mu}\rangle$ / $\langle P_{\bar{\mu}\bar{\mu}}\rangle$ $\frac{\Delta E}{E}$ = 20% $\exists$ CPT / $\nexists$ CPT	N_{ν_μ} after osc. $\exists$ CPT	$N_{\bar{\nu}_\mu}$ after osc. $\exists$ CPT	$N_{\bar{\nu}_\mu}$ after osc. $\nexists$ CPT
CERN–OPERA	21125 / 10562	0.985 / 0.972	20494	10247	10125
CERN–SK	1945 / 972	0.096 / 0.18	187	93	175
Fermilab–SK	2050 / 1025	0.096 / 0.179	197	98	183
CERN–IceCube	116679 / 58340	0.13 / 0.26	12415	6207	15168
Fermilab–IceCube	117439 / 58720	0.129 / 0.263	12496	6248	15443

Table 3: ν_μ and $\bar{\nu}_\mu$ appearance: event rate in conserved and in violated CPT parameters (100% tunnel length comparable with OPERA). The events are relative to one year data taking, as they would be without neutrino oscillation. From the first column: the total number of ν_μ and $\bar{\nu}_\mu$ events born inside detector and those whose track starts outside detector; survival probability for ν_μ and $\bar{\nu}_\mu$ under 20% energy uncertainty; final number of ν_μ and $\bar{\nu}_\mu$ events for the two CPT scenario.

1% Baseline	N_{ν_μ} after osc. $\exists$ CPT	$N_{\bar{\nu}_\mu}$ after osc. $\exists$ CPT	$N_{\bar{\nu}_\mu}$ after osc. $\nexists$ CPT	Statistical Significance σ
CERN–SK	1.9	**0.9**	**1.8 ± 1**	0.6
Fermilab–SK	2	**1**	**1.8 ± 1**	0.6
CERN–IceCube	152	**76**	**152 ± 12**	**6.1**
Fermilab–IceCube	151	**76**	**154 ± 12**	**6.3**

Table 4: ν_μ and $\bar{\nu}_\mu$ event rates considering reduced size experiment, and $\frac{\Delta E}{E}$ = 20% energy spread. It is shown the very economic setup where event rate is reduced to 1%, having considered 5% decay length tunnel, and 20% π flux intensity in *NeuWorld* experiment.

Baseline	$\langle P_{\mu\tau}\rangle$ $\frac{\Delta E}{E}$ = 10%	$N^{CC}_{\nu_\tau}$ with osc.	$N^{CC}_{\bar{\nu}_\tau}$ with osc.	$N^{CC}_{\nu_\tau} + N^{NC}_{\nu_i}$	$N^{CC}_{\bar{\nu}_\tau} + N^{NC}_{\bar{\nu}_i}$
CERN–OPERA	0.015	16	0.5	16	0.5
CERN–SK	0.962	119	59	220	110
Fermilab–SK	0.963	125	63	232	116
CERN–IceCube	0.945	36166	18083	65289	32645
Fermilab–IceCube	0.944	36363	18181	65676	32838

Table 5: Tau-AntiTau neutrinos in matter by CPT conserved-violated case. Estimated total events of charged current muon neutrino interaction in detector, conversion probabilities in matter, cross section ratio between tau-neutrino and muon neutrino, event rates for tau and anti-tau neutrino (last with both conserved and violated CPT-symmetry), and noise events by Neutral Current neutrino interactions. Note that the absence of τ or $\bar{\tau}$ appearance would lead to less than half of the event showering rate in last columns.

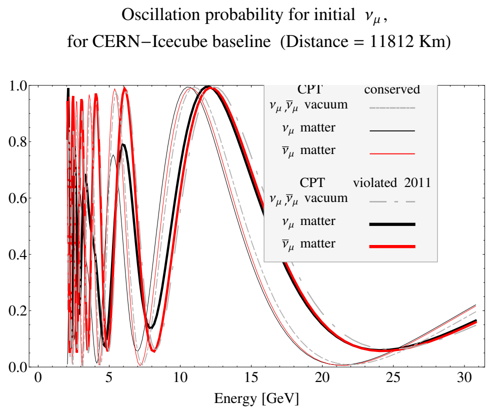

Figure 2: Muon neutrino and anti-neutrino survival probability ($P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$). There is a difference due to a slight asymmetry in the MSW term for matter effect; moreover such a discrepancy between matter and anti-matter is negligible in our energy window of interest. The FNAL-SK and FNAL-IceCube oscillations are very comparable to those from CERN because of very similar distances. Note that while crossing the Earth here and later we did not consider (as most other authors did) only the average density of Earth (respectively, $\rho = 4.5 gcm^{-3}$ for "near" SK; $\rho = 7.2 gcm^{-3}$ for "far" IceCube DeepCore), but the exact variable matter profile. Nevertheless, the vacuum and matter cases, as shown in figure, do not differ relevantly for energies higher than 10 GeV.

Table 6: Tau-AntiTau neutrinos event rates for reduced *NeuWorld* experiment, as before, to overall 1% of OPERA experiment. Statistical significance is referred both for ν_τ, $\bar{\nu}_\tau$ only detection, and for CPT cases detection. Note that the absence of τ or $\bar{\tau}$ appearance would lead to less than a half of the showering event rate.

1% Baseline	$N^{CC}_{\nu_\tau} + N^{NC}_{\nu_i}$ $\exists$ CPT $year^{-1}$	σ for ν_τ	$N^{CC}_{\bar{\nu}_\tau} + N^{NC}_{\bar{\nu}_i}$ $\exists$ CPT $year^{-1}$	σ for $\bar{\nu}_\tau$
CERN–SK	2	0.8	1.1	0.6
Fermilab–SK	2	0.8	1.2	0.6
CERN–IceCube	653	14	**326**	10
Fermilab–IceCube	657	14	**328**	10

appearance in any MINOS like CPT violation scenario, as well as a sharp probe of the appearance of many τ and $\bar{\tau}$: at least two or one at a day. This *NeuWorld* experiment may lead also to an improvement of many neutrino oscillation parameter measure [2] not discussed here, as the neutrino mass hierarchy. Such up-going neutrino beam signals in DeepCore and SuperK is completely noise free from any atmospheric neutrino ones, since the clock and packet time-windows of the sent bunches is narrow and the directionality is also very selective. The *NeuWorld* experiment is a very promising, being a very low cost one while at once offering the largest neutrino baseline test, beaming from CERN (or Fermilab) to largest neutrino detector (Deep Core) that already exist: a bending tunnel of a few percent OPERA size is

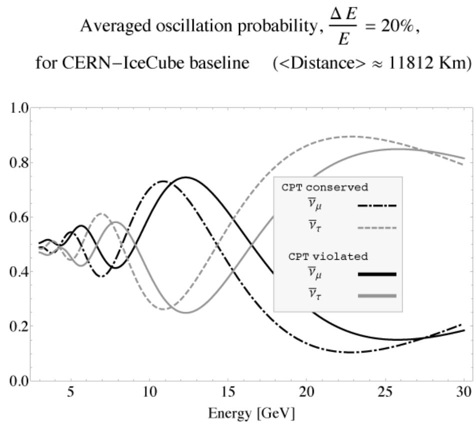

Figure 3: Averaged oscillation and survival probability, showing the average conversion smeared by neutrino energy spectra at $\Delta E/E = \pm 20\%$. The survival probability is less sharp than in the monochromatic scenario, however, as shown in Table 4, the event rate even in the framework of a minimal 1% OPERA-like *NeuWorld* experiment allows us to detect any eventual CPT violation with 6.1σ signature in one year.

just the missing tool.

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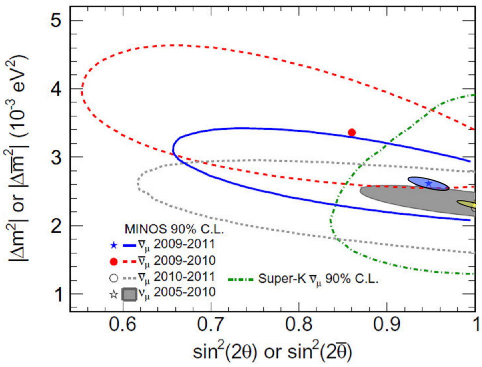

Figure 4: Neutrino and anti-neutrino muon oscillation probability in $\sin(2\theta_{23}) = 1$ and $\Delta m^2 = (2.35^{+0.11}_{-0.08}) \cdot 10^{-3} eV$ as in old data by MINOS and SK. Also the old $\bar{\nu}_\mu$ oscillation probability ([3]) into $\bar{\nu}_\tau$ CPT violated parameters was $\Delta\overline{m}^2_{23} = (3.36^{+0.45}_{-0.40}) \cdot 10^{-3}$ eV^2 and $\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$. On the contrary, the recent parameters are more comparable with the CPT conserved ones [4]: $\Delta\overline{m}^2_{23} = 2.62^{+0.31}_{-0.28} \cdot 10^{-3}$ eV^2, $\sin^2(2\overline{\theta}_{23}) = 0.945$. The early MINOS discordance was about 2.5 sigma, but the most recent one is within one sigma consistent with the CPT conserved case. Our beaming across the Earth might reach a discrimination described somehow by the inner smaller ellipses, whose extension at 6 sigma may disentangle even last eventual MINOS tiny CPT discordance.